Introduction of Structural Health Monitoring to Civil Engineering Education

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Abstract

This paper describes the development of a Structural Health Monitoring (SHM) Education Unit; its initial implementation and assessment at Louisiana State University (LSU) and the University of Louisiana-Lafayette (UL-Lafayette) during the 2016-17 Academic Year; and its subsequent re- implementation and assessment during the 2017-18 Academic Year at these institutions plus its initial implementation at four partner institutions – Case Western Reserve University, Tuskegee University, University of North Florida and Virginia Tech. The SHM Education Unit encompasses the Fundamentals Education Subunit and the Applications Education Subunit.

The Fundamentals Education Subunit consists of an introductory and four content online modules whereas the Applications Education Subunit consists of two content online modules, a SHM system design/evaluation module and a SHM instrumentation model demonstration. Using a pedagogical model developed during the project, the former Subunit is implemented in two classes of a structural analysis course whereas the latter Subunit is implemented in two classes of a reinforced concrete design course. The results of readiness tests and student assessments demonstrate the effectiveness of the content and the pedagogical model to engage students and teach SHM fundamentals and practices.

1. Introduction

While civil and environmental engineering (CEE) undergraduate curricula generally incorporate laboratory courses in such topics as material testing, fluid mechanics, and geotechnical engineering, among others, the subject matter is often limited to either an experimental demonstration of theoretical principles or to conducting standard laboratory tests. Field measurements and monitoring techniques and practices may be touched upon but are rarely addressed in any depth. While the content of traditional laboratory courses and practices still have relevance and merit in the preparation of civil and environmental engineering professionals, there is a growing recognition of the importance and prevalence of field monitoring and measurements (FMM) in current and future engineering practice. The results of two surveys of CEE professionals described in the following paragraphs demonstrated the accuracy of this observation.

Two separate but related surveys of CEE professionals were conducted to determine the perceived importance and need for FMM education at the undergraduate level. One survey was directed at geotechnical engineering professionals through brief articles published in geotechnical engineering newsletters distributed nationally. The second survey was directed to a broader sampling of CEE professionals by email solicitations to local consulting firms, the Louisiana Department of Natural Resources (LDNR), the Louisiana Department of Transportation and Development (LDOTD), the Louisiana Transportation Research Center (LTRC), and out of state transportation research organizations. The three essential questions posed by the survey were: the current perceived importance of FMM; the future perceived importance of FMM; and the perceived enhancement of the undergraduate CEE curriculum with the addition of FMM education.

A total of 13 professionals responded to the geotechnical engineering survey. While this was a very modest response, the results were generally very consistent and are considered to be reasonably representative. Forty-three professionals from a broader sampling of CEE sub disciplines completed the second survey. The respondents were somewhat skewed toward structural engineering (44%). The years of practice of the respondents varied from 0-2 years to over 31 years. Respondents with 6 or more years of experience varied from 86% of the broader CEE respondents to 77% of the geotechnical engineering respondents. Only 9% of the CEE respondents and 8% of the geotechnical engineering respondents reported that they had any structured FMM education (a formal course or applicable content in one or more courses) at the undergraduate level. Twenty-four percent and twenty five percent of the CEE and Geotechnical respondents, respectively, indicated that the lack of a structured FMM education made them less likely to employ FMM techniques.

The relative consistency of the results of these two surveys, one local and directed to the broader CEE community and one national and directed to a specific CEE sub discipline, suggests that the results are representative of the CEE profession at large. Based on that contention, it is observed that greater than 62% of the CEE respondents and 92% of the geotechnical respondents judged current FMM practice to be of significant or extreme importance while 86% and 89% of the CEE and geotechnical respondents, respectively, judged the future importance to be of significant or extreme importance. Further, 61% of the geotechnical engineering and 47% of the CEE respondents, concluded that incorporating FMM education into the undergraduate CEE curriculum would provide a significant or extreme enhancement to the curriculum. In the judgment of the authors, these results support both the **importance** and **need** for FMM education at the undergraduate level in CEE. In the open-ended response opportunity provided in the surveys, several of the respondents expressed concern over incorporating FMM education in an already packed curriculum.

Reinforcing the need to incorporate FMM principles and practices into the CEE curriculum are the accreditation criteria of the Accreditation Board for Engineering and Technology (ABET) and the Body of Knowledge requirements of the American Society of Civil Engineers (ASCE) for undergraduate programs. ABET promulgates General and Program Accreditation Criteria [1] that include the following expected learning outcomes: an ability to design and conduct experiments, as well as analyze and interpret data; an ability to identify, formulate and solve engineering problems; and an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice. More directly applicable to the work presented here are the Body of Knowledge (BOK) [2] requirements. These encompass learning outcomes directly related to the need for the development of experimental and data analysis skills. A survey of practicing professionals [3] resulted in a list of similar expectations as those in the BOK for students entering the workforce.

Given the desirability, if not the need to incorporate FMM education in the undergraduate CEE curriculum, the question is– how can the curriculum be revised to incorporate and address relevant field monitoring and measurements practices? In agreement with the reservation of several of the survey respondents cited earlier, one fact is clearly evident– adding new courses to an already "packed curriculum" is a non-starter. Given the constraints of the existing curriculum, a teaching model that would allow the meaningful introduction of FMM principles and practices without significantly altering the content of the current curriculum or disrupting the existing courses was needed. With the support of a National Science Foundation grant, such a model was developed and introduced at Louisiana State University and University of Louisiana-Lafayette in Fall 2016. A description of the model and the findings of the NSF project follows.

2. Project Rationale, Goal and Objectives

Attacking the entire scope of FMM principles and practices in the CEE curriculum was not feasible nor appropriate given the need to first develop an appropriate and effective teaching model. Thus, consistent with the expertise and experience of the three project investigators, the NSF project focused on a pilot effort to introduce Structural Health Monitoring fundamentals and practices into the sequence of required structural engineering courses– structural analysis and reinforced concrete design.

Given this approach, the main goal of the project was to develop a model instructional program that can be used to educate CEE students in the fundamental principles and technology of structural health monitoring and measurements (SHM) and to utilize monitoring technologies and SHM data to evaluate performance and behavior, analyze problems and design structural engineering systems. This goal was to be achieved by meeting the following objectives:

- Developing and implementing a modular-based transportable structural engineering SHM Education Unit for CEE students in a manner that enhances the students' achievement of the traditional expected learning outcomes for the two affected courses.
- Developing a community of scholars that has an interest in and will contribute to the further development of SHM instructional materials.

3. Student Learning Outcomes

It is expected that students will elevate their learning along the revised Bloom's Taxonomy [4] by achieving the following expected learning outcomes:

- Students will be able to demonstrate on conventional examinations for each online education module (termed Foundational Education Modules–FEMs) and Discipline-Specific Education Modules–DSMs) that they have achieved at least a 80% level of comprehension of the body of knowledge at the **"applying"** level of learning in accordance with the revised Bloom's Taxonomy.
- Using rubrics to be developed as a part of the NSF project, students will be able to demonstrate for each

assignment module that they can use SHM data in the analysis of a problem or the preliminary design of an SHM system at least at an 80% level of competency at the **"analyzing"** or **"evaluating"** or **"creating"** levels of learning in accordance with the revised Bloom's Taxonomy.

- Students will achieve the established expected learning outcomes for the affected courses at an equal or higher level of achievement than their historical achievement.

In practice, specific expected learning outcomes were developed for each fundamentals and assignment modules. These outcomes conform to the cognitive levels of learning stated above.

4. Project Personnel

Two of the three project investigators had expertise in structural engineering and extensive experience in Structural Health Monitoring. The other project principal had experience and expertise in FMM in geotechnical engineering as well as educational development. Supplementing the project principals was an Advisory Panel of SHM experts drawn from academia, state departments of transportation, and private practice. Guidance in assessment of the outcomes was provided by an external evaluator from a major university. Technical and administrative support was provided by an LSU graduate research assistant, LSU undergraduate student assistants, and an LTRC Multi-Media Specialist.

The scope of the project also included the implementation and assessment of the SHM Education Unit at four partner institutions beginning in Fall 2017: Case Western Reserve University; Tuskegee University; University of North Florida; and Virginia Tech. The activities at each of these institutions were directed by a structural engineering or structural mechanics faculty member with expertise and interests in SHM.

5. SHM Education Unit Structure

The organization and structure of the SHM Education Unit and the Fundamentals and Applications Education Subunits are graphically depicted in Figure 1. FEM1-FEM4 and SEM1-SEM2 are basically content modules prepared using content drawn from the engineering literature. FEM0 is an introductory or rationale module that introduces the students to the what, why and how of the SHM educational experience. Essentially lacking any fundamental knowledge and/or understanding of SHM principles and practices on the part of the students, these modules primarily addressed the lower levels of cognitive learning. Of particular importance to the development of the content modules was the work of Bisby [5] who actually developed a SHM educational module for ISIS Canada. Unique to our effort are the two assignment modules (SAM1-SAM2) which require students to work at the higher levels of cognitive learning consistent with the stated Student Learning Outcomes. SAM1 requires students to either evaluate or qualitatively design a SHM system to assess some particular aspect of a structure's behavior or health. SAM2 consists of a real time demonstration of the behavior of an undamaged and damaged SHM instrumented beam model. Students are required to make qualitative predictions of the behavior of the beam in each circumstance.

6. SHM Education Unit Pedagogical Model

Constrained by limitations of class time and the objective of preventing negative impacts if not enhancing the achievement of the traditional student learning outcomes in the relevant target courses– structural analysis and reinforced concrete design, it was concluded that no more than two class periods could be devoted to SHM education in any one course. Given that constraint and the scope and amount of content judged to be necessary for a meaningful educational experience, the project adopted a "flipped classroom" type approach. That is, in advance of a classroom discussion session, students reviewed the content modules online that were provided in both PowerPoint and eLearning formats. After completing their review of the module, they completed a readiness examination for which they had to achieve a score of 80% or better. As a final step, they submitted their response/answer to a question which was to be the subject of discussion in a subsequent class session. On the day of the classroom discussion, students were formed into groups of 2-4 and compared their responses to the assigned discussion question after which the instructor coordinated the discussion by calling on a number of student groups to share their collective response to the assigned discussion question. At the conclusion of the discussion session which was generally limited to no more than 15 minutes, students were asked to submit a "one minute paper" in which they listed any lingering questions or concerns relative to the discussion topic. The instructor conducted a quick review of the papers, attempting to identify particularly similar and important questions and/or concerns. The session was then concluded with the instructor addressing the lingering questions and/or concerns. Of importance in adopting this model is time management. The duration for each of the in-class subactivties will have to be adjusted depending on classroom session duration. It was found that as many as three discussion questions from a like number of education modules could be addressed in one classroom session. This roughly translates into 25 minutes per modules for a class that meets three times a week, and 40 minutes per module for a class that meets twice a week.

After each of the classroom discussion sessions, the students were asked to complete an online assessment survey for each of the modules. Figure 2 graphically depicts the pedagogical model developed and implemented specifically for the SHM Fundamentals Education Subunit. An identical model was used for the two structural engineering modules of the Applications Education Subunit (SEM1 and SEM2) but the scope and objectives of the two assignment modules (SAM1 and SAM2) of that Subunit required a somewhat alternative approach. In advance of the students' initiating their involvement in the SHM Education Unit, they were briefed during a short in-class presentation and provided with a detailed schedule of deadlines and activities.

7. Some Selected Implementation Issues

Since project principals did not necessarily teach the relevant implementation course during any given semester, cooperation of the course instructor was needed. That cooperation entailed providing two class periods and time in another class for the briefing cited above. In addition, provision for the inclusion of a description of the planned educational experience in the course syllabus as well as course credit for the experience– extra credit or some percent of the course grade. We recommended no more than 3% of the class grade.

In the case of the implementation at LSU, all the relevant course materials were embedded in Moodle, an open source instructional management system. At ULL-Lafayette, students accessed the course materials via a specially designed student website. Both approaches worked but the former more seamlessly and with less effort. One of the objectives of the investigators was to either eliminate or minimize the barriers faculty would face in adopting and implementing the SHM Education Unit at their respective institutions.

In meeting with our institutional partners, we learned that certain local circumstances dictated alternative implementation approaches. One example– multiple sections of the initial implementation course meant that some of the students in the follow-up course (also multiple sections) would not have the proper preparation. Thus, they have chosen to implement the entire Unit in an elective course entitled "Bridges, Builders and Society."

To assist our institutional partners in planning and implementing the SHM Education Unit at their institution, the project investigators conducted two planning and implementation workshops– one online for the Fundamentals Education Subunit and one face-to-face for the Applications Education Subunit.

8. Preliminary Assessment Results and Observations

Based on the experience gained from implementing the proposed SHM Unit at LSU and UL-Lafayette, the authors were able to make some observations on several aspects of the proposed effort.

First, it is evident that students were very receptive to the introduction of SHM. Many questions were raised during the discussion sessions about why SHM is not currently included in the CEE curriculum, how can they learn more about it and when will they be able to use the equipment in the application modules.

It was also clear that the proposed pedagogical model engages the students in an active learning environment that fosters larger participation from the students. Further, post-treatment survey results revealed that the time it takes the students to review the material is reasonable (1.5 hours per module on average).

Finally, the content of the modules was rated good-very good on average, which is acceptable but leaves room for improvement. The authors are continuously improving the content of the modules as well as the quality of the delivery of the modules to ensure better student engagement and achievement level of learning outcomes.

9. Future Dissemination Efforts

Following the 2017-18 AY implementation period, a national campaign will be initiated to promote adoption of the SHM Education Unit at other institutions. Adopters will be provided access to all the content materials and supported via personal communications and online workshops. At the present time, interested faculty members are invited to http://www.ltrc.lsu.edu/nsf/ to view details about the project as well as register to access guidance and education documents.

10. Concluding Remarks

While one of our project objectives was to establish a community of scholars that would not only adopt the SHM Education Unit but contribute to its improvement and in some instances apply the pedagogical model to the development of FMM education units in other areas of CEE, that objective is yet to be realized. Such an effort will be pursued as an important companion component of the dissemination process described above.

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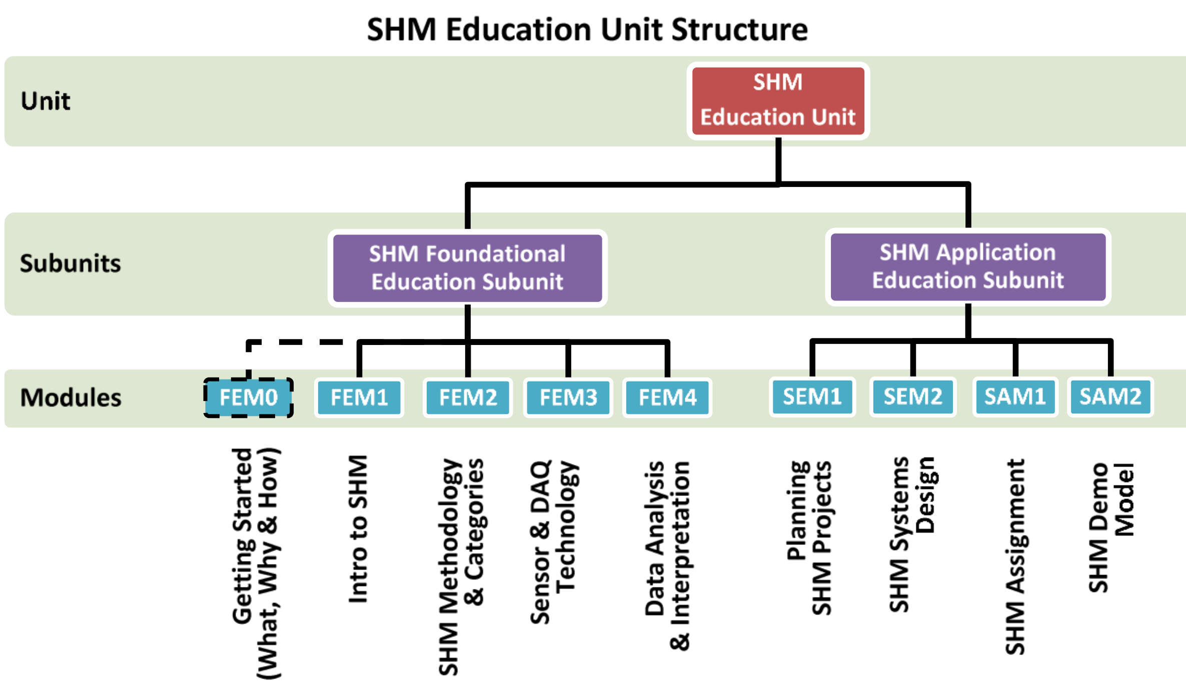

Fig. 1 Overview of proposed SHM Education Unit

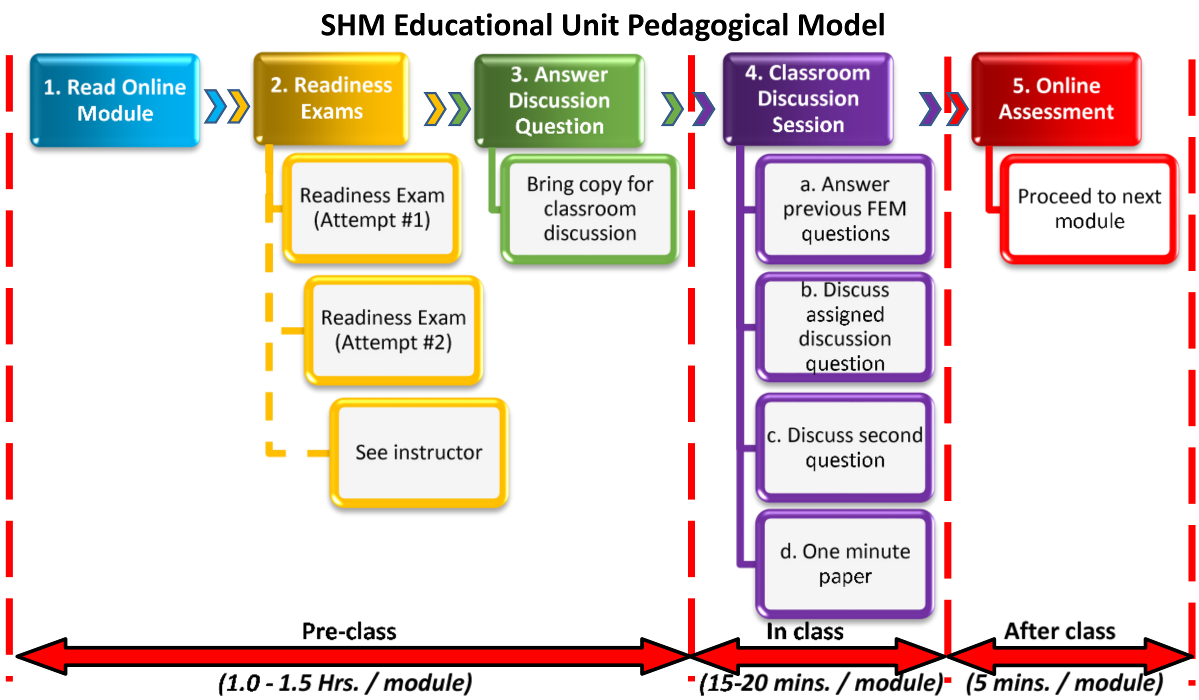

Fig. 2 Proposed pedagogical model